GEOPHYSICAL RESEARCH LETTERS, VOL. 36, L21104, doi:10.1029/2009GL040585, 2009

Self-consistent evolution of auroral downward-current region ion outflow and moving double layer

K.-J. Hwang,[1,2] R. E. Ergun,[3,4] D. L. Newman,[5] J.-B. Tao,[4] and L. Andersson[3]

Received 15 August 2009; revised 24 September 2009; accepted 7 October 2009; published 7 November 2009.

[1] Vlasov simulations have been performed to investigate the development and evolution of the parallel potential drop, often structured as a localized double layer (DL), electron phase-space holes, and ion perpendicular heating, resulting in ion outflow in the auroral downward-current region. We focus on the feedback between a moving DL and heated ions, suggesting a self-consistent model: the heated ions regulate the evolution of the DL which controls the level of ion heating and, consequently, the outflow rate. Strongly heated ions forming conics are found in agreement with in-situ observations. The intensification and widening of the DL develops with time, and the DL eventually weakens due to a reduction in the background population resulting from excessive ion heating. **Citation:** Hwang, K.-J., R. E. Ergun, D. L. Newman, J.-B. Tao, and L. Andersson (2009), Self-consistent evolution of auroral downward-current region ion outflow and moving double layer, *Geophys. Res. Lett.*, *36*, L21104, doi:10.1029/2009GL040585.

1. Introduction

[2] The auroral downward-current region (DCR) is characterized by downward-pointing $\mathbf{E}_{\parallel}$ (the electric field parallel to the geomagnetic field $\mathbf{B}$), up-going beams of field-aligned electrons, ion conics, broad-band electrostatic low-frequency (BBELF) waves, and electron phase-space holes [*Marklund et al.*, 1997; *Carlson*, 1998; *Ergun*, 1998; *Moncuquet et al.*, 2002]. The auroral DCR has attracted scientific attention because ion outflow, defined as the transport of Earth's ionospheric ions to the magnetosphere, is commonly observed in the DCR despite the fact that the parallel electric field is pointing earthward, which is expected to retard the upward ion motion. *Gorney et al.* [1985] explained this phenomenon with a, so-called, ion-pressure cooker model whereby the downward electric field confines ions in a region of wave-particle interactions until the perpendicular energy of ions increases enough for their upward mirror force to exceed the retarding downward force of $\mathbf{E}_{\parallel}$.

[3] One long-standing question about the DCR is how the parallel potential drop is distributed along the DCR flux tube, i.e., whether the potential drop is extended smoothly along the field line, or formed as highly-localized potential steps, known as double layers (DLs). This is important in modeling DCR ion outflow, as it affects the heating profile of a function of altitude.

[4] Motivated by direct observations of large-amplitude $\mathbf{E}_{\parallel}$ pulses interpreted as localized (several tens of an electron Debye length, λ_D), moving (in the anti-earthward direction) DLs responsible for particle accelerations and wave turbulence [*Ergun et al.*, 2003; *Andersson et al.*, 2002], and a numerical simulation of a DL [*Newman et al.*, 2001], *Hwang et al.* [2008] performed a test particle simulation to investigate how these moving DLs can affect DCR ion outflow. They proposed that dynamic DLs with incorporated heating profiles immediately above and below each DL might change the classical Gorney's ion-pressure cooker picture for the mechanism of ion outflow by implying that an intense wave power above the moving DL efficiently evacuates a DCR flux tube. Although all the parameters about DLs and their heating profiles in their study are selected among plausible parameter ranges based on in-situ observations [*Karlsson and Marklund*, 1996; *Marklund et al.*, 1997; *Elphic et al.*, 2000; *Marklund*, 2001; *Andersson et al.*, 2002; *Ergun et al.*, 2003] and dynamic simulation results [*Newman et al.*, 2001; *Singh and Khazanov*, 2005], their non-self-consistent treatment of DLs limited what could be inferred regarding the evolution of a DCR flux tube, and feedback between the DLs and heated ions.

[5] In this paper, we present a numerical simulation of a DCR DL that illustrates how the structure of a self-consistent DL is affected by ion heating when the heating rate is controlled by the evolving characteristics of the DL and of the electron phase-space holes generated by the DL. Parameters of the model are compromised in order for the simulations to be numerically feasible for manifesting the heating effect, but yet this study contributes to understanding specific processes that can influence DCR ion outflow through a simplified numerical model that contains key nonlinear interactions allowing feedback between particles and fields.

2. Simulation Methodology

[6] This study is based on the numerical integration of the Vlasov-Poisson equations in one spatial dimension ($z \| \mathbf{B}$) under the assumption of infinitely magnetized electrons in $z{-}v_z$ phase space and gyrotropic H^+ ions in $z{-}v_z{-}v_{\perp}$, phase space. Open-boundary conditions are applied at both ends of the spatial domain [*Newman et al.*, 2008a]. Throughout the domain a constant electric field E_0 is added to the self-consistent electric field $E(z, t)$ calculated from Poisson's equation at each time step, with

[1]NASA Goddard Space Flight Center, Greenbelt, Maryland, USA.
[2]University of Maryland at Baltimore County, Baltimore, Maryland, USA.
[3]Laboratory of Atmospheric and Space Plasmas, University of Colorado at Boulder, Boulder, Colorado, USA.
[4]Department of Astrophysical and Planetary Sciences, University of Colorado at Boulder, Boulder, Colorado, USA.
[5]Center for Integrated Plasma Studies, University of Colorado at Boulder, Boulder, Colorado, USA.

0094-8276/09/2009GL040585$05.00

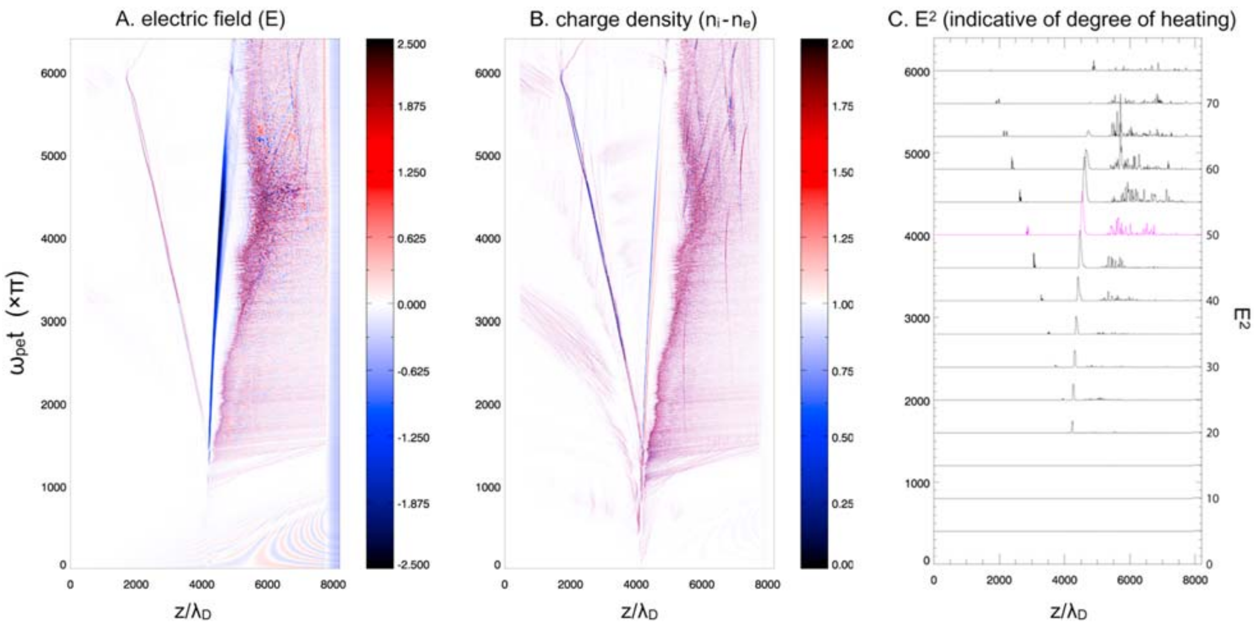

Figure 1. (a) Time history of E and (b) charge density, $n_i - n_e$ along the simulation domain, $z\lambda_D$ (x-axis) and run time, $\omega_{pe}t$ (y-axis, $\times\pi$) for $n_R/n_L = 0.8$, $B_R/B_L = 0.2$, and $H = 1.2 \times 10^{-2}$. A moving DL to the right boundary, initially created at the center of the simulation domain, is represented by a blue (negative E) line in Figure 1a and a parallel bipolar charge-separation layer in Figure 1b. Electron phase-space holes are represented as nearly horizontal streaks on the high-potential side of the DL. (c) Temporal variations of E^2 (each horizontal line corresponds to $E^2 = 0$) are shown at intervals of $400\pi\omega_{pe}^{-1}$. The magenta line indicates the intensity of heating along the simulation domain at the run time for the results presented in Figures 2b and 2c.

the sum applied to both electrons and ions. The gravitational force, $-m_i g$, and the magnetic mirror force, $-\mu\frac{dB}{dz}$, are applied to ions only, where $\mu = \frac{m_i v_\perp^2}{2B}$ is adopted as a proxy for the perpendicular ion velocity in the simulations. The resulting Vlasov equations take the following form:

$$\begin{aligned}\frac{\partial f_e}{\partial t} + v_z\frac{\partial f_e}{\partial z} - \frac{e}{m_e}[E(z,t)+E_0]\frac{\partial f_e}{\partial v_z} &= 0\\ \frac{\partial f_i}{\partial t} + v_z\frac{\partial f_i}{\partial z} + \frac{e}{m_i}\left[E(z,t)+E_0-m_i g-\mu\frac{dB}{dz}\right]\frac{\partial f_i}{\partial v_z} &= 0\end{aligned}.$$

[7] An initial ion distribution $f_i = f_i(v_z, \mu, z)$ consisting of a non-drifting ionospheric component is represented by an isotropic Maxwellian distribution in velocity multiplied by a Boltzmann factor in z so as to be quasi-stationary when subjected to the combined electric, gravitational, and magnetic-mirror forces. The initial electron distribution $f_e = f_e(v_z, z)$ consists of two distinct Maxwellian populations: a drifting, cold ionospheric component (75% of the total f_e at the center of the simulation box) which has a density gradient along z accordingly to the quasi-stationary Boltzmann-distributed ions, with the remaining 25% comprising a non-drifting, uniformly-distributed, supra-thermal plasmasheet component (see *Newman et al.* [2008a] and *Andersson et al.* [2008] regarding the effect of the suprathermal electron population on the stability of a DL). This suprathermal component is given a temperature 36 times that of the cold drifting component. The time-invariant B is assumed to decrease exponentially with z for simplicity.

[8] All physical quantities are normalized as follows: length is normalized by λ_D, time by the reciprocal of the electron plasma frequency, $1/\omega_{pe}$, velocity by the drifting electron component's thermal velocity, $v_{e,th}$ mass by the electron mass, m_e, electric field by $m_e v_{e,th}\ \omega_{pe}/e$, and magnetic field by the magnetic intensity at $z = L_z/2$, where L_z is the size of a simulation domain (either 4096 λ_D, or 8192 λ_D). Two important parameters are the ratio of density at $z = L_z$ (the right boundary in Figure 2) and $z = 0$ (the left boundary) designated n_R/n_L, and the ratio of magnetic intensity at the two boundaries designated B_R/B_L. The latter determines the magnetic mirror force, while the former enters in the constant values of E_0 and g that are derived to meet the initial requirements of quasi-neutrality and net force balance for each species.

[9] The perpendicular heating of ions is implemented by broadening f_i in $v_\perp$ (or μ) while conserving the density at each ion-iteration step: $f_i(\mu)$ before heating $\rightarrow g'(\mu) f_i(g(\mu))$ where $0 < g'(\mu) < 1$ after heating with a constraint, $\int f_i(\mu)d\mu = \int g'(\mu)f_i(g(\mu))\, d\mu$. We assume that the heating rate scales as the local electric potential energy, i.e., $g'(\mu) = [1 + (\text{heating constant}, H) \times E^2]^{-1}$, based on both observations and simulations [*Ergun et al.*, 2001; *Andersson et al.*, 2002; *Moncuquet et al.*, 2002; *Newman et al.*, 2001, 2008a] indicating that the level of intense wave turbulence is proportional to the parallel potential drop in the DCR. The two-dimensional structure of electron phase-space holes, acting as an ion collider, might provide the linking of the local parallel electric field and the perpendicular heating rate [*Ergun et al.*, 2003; *Newman et al.*, 2007]. Note that the heating constant, H, numerically parameterizes the intensity of the ion perpendicular heating for a given E.

3. Simulation Results

[10] Figure 1 shows the time history of E (Figure 1a) and charge density, $n_i - n_e$ (Figure 1b) along the simulation

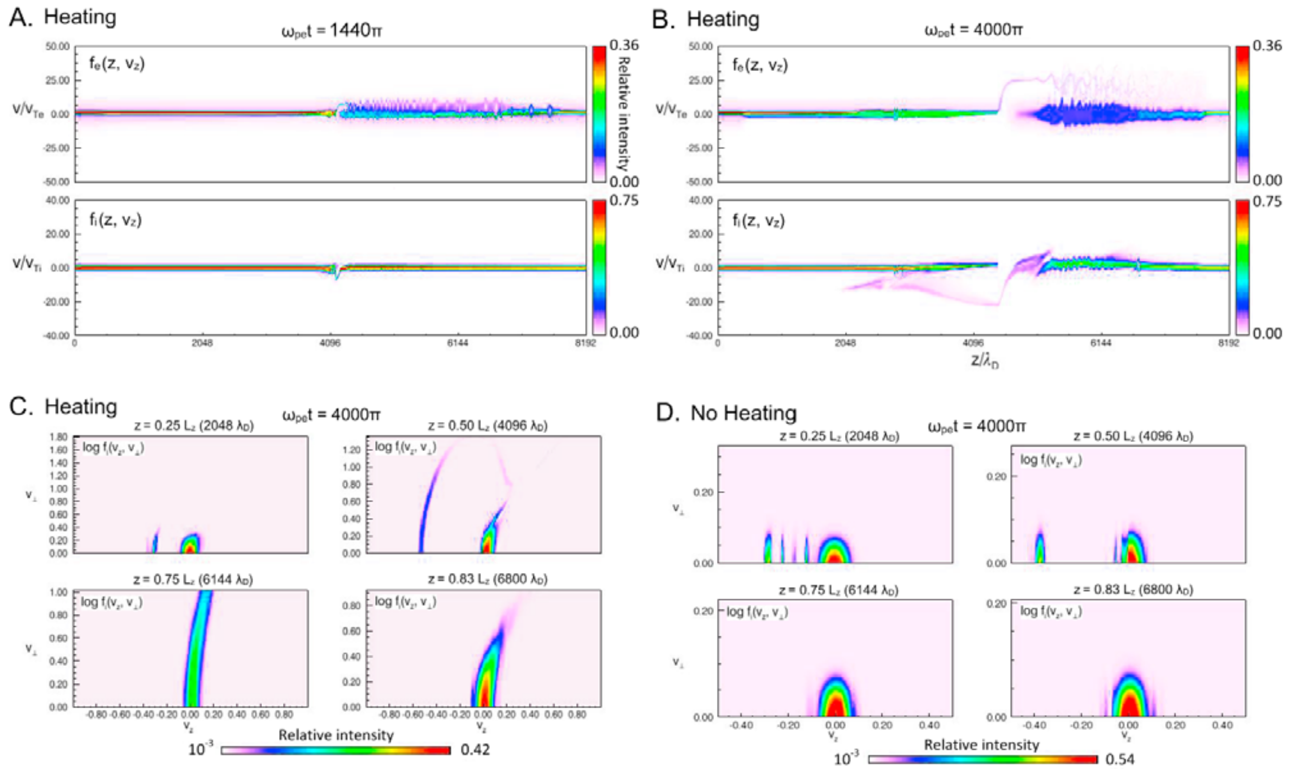

Figure 2. Electron and ion distributions at $\omega_{pe}t$ = (a) 1440 and (b) 4000. (c) Ion two-dimensional distributions at z = (0.25, 0.5, 0.75, and 0.83) × L_z, from upper left to lower right (note z_{DL} = 0.56). Parallel and perpendicular velocities to B are shown in x- and y-axis, respectively. The mirroring of the down-going ion beams (top right) and ion conics above the DL are shown. Ion distribution functions of no heating run (H = 0, (d) shows neither particle perpendicular heating nor a conical distribution.

domain, z/λ_D (x-axis) and run time, $\omega_{pe}t$ (y-axis, $\times\pi$) for n_R/n_L = 0.8, B_R/B_L = 0.2, and $H = 1.2 \times 10^{-2}$. An initial density gradient throughout the simulation domain generates a short-lived, global, Langmuir fluctuation until $\omega_{pe}t = 1000\pi$ as seen in Figure 1a. A charge-neutral density depletion imposed at the center of the simulation domain onto the initially force-balanced, quasi-neutral plasma of drifting electrons moving from low to high z(to higher altitudes), carrying a downward field-aligned current and stationary ions, acts as a seed for an upward-moving DL. The trace of the DL is identified as a blue (negative E) line in Figure 1a and a parallel bipolar (blue and red, i.e., negative and positive charge-separation layer) signature in Figure 1b. As the DL potential develops with time, electrons accelerated by the DL onto the initial drifting electrons drive two-stream-unstable wave to a nonlinear level, at which stage wave saturation by trapping streaming electrons are manifested as electron phase-space holes [*Goldman et al.*, 2003; *Newman et al.*, 2001]. These electron phase-space holes appear as nearly horizontal streaks (due to their high velocity) above a standoff distance [*Newman et al.*, 2008b] from the DL, on the high-potential side, in Figures 1a and 1b. The kinetic-Buneman-origin structure [*Goldman et al.*, 2003] moving to the left boundary (seen as oblique lines) heats the ions below the DL, facilitating the mirroring motion of the ions, but destabilizes the run when it reaches the left boundary. Figure 1c shows temporal variations of E^2 (indicative of the degrees of the heating in this study) at intervals of $400\pi\ \omega_{pe}^{-1}$.

[11] The snapshots of the electron (Figures 2a, top and 2b, top) and ion (lower) phase-space distributions along z, $f_{e,i}(z, v_z)$, at $\omega_{pe}t = 1400\pi$ (Figure 2a) and 4000π (Figure 2b) illustrate the evolution of the system: the growth of a moving DL located at about z/λ_D = 4186 and 4588 (z_{DL} = 0.51 and 0.56 L_z), in Figures 2a and 2b, respectively, accelerated electron and ion beams (light blue streaks at around $v_{z,e}$ = +25 and $v_{z,i}$ = −22 in Figure 2b, above and below the DL, respectively), electron phase-space holes shown as a string of circular (water-drop-like) structures in Figure 2a, and irregular faint ripples due to their high speed in Figure 2b, for $f_e(v_z > 0, z > z_{DL})$, and heated ions (seemingly-diffused ions from the core at $v_{z,i} = 0$ in Figure 2b, compared to Figure 2a).

[12] Figure 2c shows the ion two-dimensional distribution, $f_i(v_z, v_\perp)$ at z = (0.25, 0.5, 0.75, and 0.83) × L_z at the same time as Figure 2b, compared to that of no heating run (H = 0, Figure 2d). Below the DL (Figure 2c, top), the downward ion beams generated by the DL are distributed as conical shape, and mirrored ion beams are shown immediately below the DL (Figure 2c, top right), as a result of perpendicular heating and the magnetic mirror force. Initially stationary ions are also affected by these local heating processes, and they too exhibit features of a conic, although to a lesser extent. Above the DL (Figure 2c, bottom), bulk ions are strongly modified, having been continuously heated by the electron phase-space holes that are rapidly passing by them. High-v_z components in these distributions are those which have been first heated when they traverse the DL. Following their heating by the DL, the ions are heated further by electron phase-space holes above the DL. These

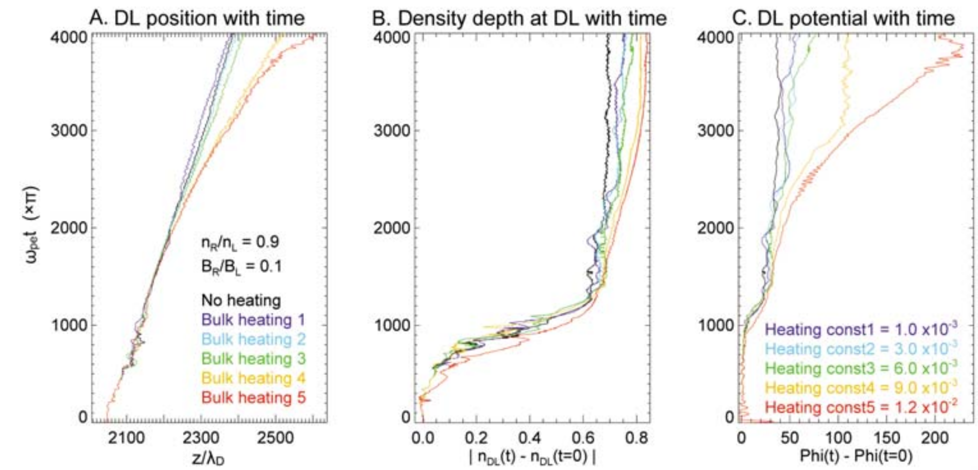

Figure 3. Summary of the parametric simulation runs of the ion perpendicular heating: (a) the velocity of DL, (b) density dip at the DL, and (c) potential across the DL with run time. The degrees of the heating rate applied to the ions are indicated by a series of different colors, and by different H values labeled in the rightmost plot.

ion-conic distributions and their variations with altitude correspond well to in-situ observations [*Moncuquet et al.*, 2002; *Hwang et al.*, 2006] and previous numerical studies [*Hwang et al.*, 2008]. Figure 2d shows that, as expected, in the absence of perpendicular particle heating, no conical distributions form.

[13] The most interesting feature to be noted in Figure 1 is that the DL intensifies and widens with time until an excessive decrease in ion fluxes into the DL from the upstream side quenches this intensification, resulting in the eventual weakening of the DL. To quantify the effect of ion perpendicular heating on the evolution of the DL, a set of six simulation runs (with the domain size of $L_z = 4096\ \lambda_D$) are performed, differing only in the value of H. Figure 3 shows the DL location in the simulation domain, ion density depletion at the DL, and potential across the DL along the horizontal axis in Figures 3a, 3b, and 3c, respectively, with time increasing along the vertical axis. The slope of the trace of the DL location in Figure 3a indicates the velocity of the DL. The black line corresponds to the simulation run with no heating, and the violet, sky blue, green, yellow, and red lines correspond to simulations with different heating constants (in the order of low-to-high heating) as indicated by the legend in Figure 3c. These parametric runs demonstrate that (1) the speed of a DL increases with heating, which might be explained as the self-adjusting behavior of the DL in order to satisfy the Langmuir condition in the frame of the DL [*Newman et al.*, 2008b], and (2) as a higher heating is applied to the ions, a DL with a deeper density depletion and larger potential develops. These qualitative trends with respect to the heating are consistent among other sets of simulation runs differing in the simulation domain size, grid size, or model parameters (not shown).

4. Discussion

[14] Results from our parametric simulation study suggest a self-consistent feedback between a DCR DL and ions that are subject to the perpendicular heating which, in our numerical scheme, is implemented by using a term proportional to the local parallel electric field squared as a proxy for the heating rate. The key steps in this self-consistent evolution are as follows: (1) initially, a DL seeded at the local density dip deepens due to the presence of the relative electron-ion motion (i.e., current) [*Goldman et al.*, 2003; *Newman et al.*, 2001]. (2) Electron holes generated by the DL as well as the DL itself have structure perpendicular to B in higher dimension and the associated perpendicular electric fields impart perpendicular kinetic energy to the ions (not implemented in this study, but assumed in the heating algorithm). (3) The perpendicularly heated ions experience a strong mirror force that increases the flow of ions away from the DL, which initially enhances the growth of the DL (physically, a decreasing density at the DL requires an increasing DL potential, via the current continuity, which results in higher perpendicular heating to ions).

[15] Figure 1 shows that this trend eventually ceases when an excessive loss in upstream ions of the DL (as a result of ever increasing heating) cannot support further intensification of the DL, and in fact results in the quenching of the DL. This can be qualitatively explained in the context of the Langmuir condition: When the ions above the DL start to heat and become mirrored upward, the DL increases its velocity in order to entrain more ions and counter the reduction in the flux of ions into the DL, and the potential across the DL increases to keep the electron pressure difference across the DL approximately constant, in order to satisfy the Langmuir condition in the new frame of the moving DL [*Newman et al.*, 2008b]. However, if the ion density above the DL becomes too much decreased so that the total pressure balance on both sides of the DL cannot be recovered by such DL behaviors, the Langmuir condition breaks down, and a stable DL is no longer supported.

[16] Previous numerical simulations [*Hwang et al.*, 2008] implied the significance of a supply of a source population in controlling DCR ion outflow, suggesting that consecutive DLs would keep producing a significant ion outflow, if there is an additional supply of a source population drifting into the DCR flux tube. Although only a single DL is implemented in our present study, it is demonstrated that the

heated ions regulate the evolution of the DL which controls the level of ion outflow, and eventually decays due to an insufficient ion flux into the DL.

[17] Another interesting feature observed in Figure 2b is the ion hole, near $z/\lambda_D = 6700$. The traces of such structures are seen in Figure 1c as the nearly vertical streaks on the high-potential side of the DL. They appear as a result of the interaction between electron phase-space holes and local plasma inhomogeneities such as the density gradient. *Newman et al.* [2008a] have studied this ion-hole-like signature that gives rise to a large disturbance of the DL at the time of its arrival to the DL, thereby affecting the stability of the DL. Although our observation of two coexisting species of phase-space holes is similar to the in-situ observation reported by *Cattell et al.* [2002], the microphysical argument about this observation is beyond the scope of this paper.

[18] **Acknowledgments.** Authors appreciate valuable comments from Martin V. Goldman. This study was supported by NSF grant ATM0503314, and NCAR computing resources.

References

Andersson, L., R. E. Ergun, D. L. Newman, J. P. McFadden, C. W. Carlson, and Y.-J. Su (2002), Characteristics of parallel electric fields in the downward current region of the aurora, *Phys. Plasmas*, *9*, 3600.

Andersson, L., D. Newman, R. Ergun, and M. Goldman (2008), Influence of suprathermal background electrons on strong auroral double layers: Observations, *Phys. Plasma*, *15*, 72,901.

Carlson, C. (1998), FAST observations in the downward auroral current region: Energetic upgoing electron beams, parallel potential drops, and ion heating, *Geophys. Res. Lett.*, *25*, 2017.

Cattell, C., L. Johnson, R. Bergmann, D. Klumpar, C. Carlson, J. McFadden, R. Strangeway, R. Ergun, K. Sigsbee, and R. Pfaff (2002), FAST observations of discrete electrostatic waves in association with down-going ion beams in the auroral zone, *J. Geophys. Res.*, *107*(A9), 1238, doi:10.1029/2001JA000254.

Elphic, R., J. Bonnell, R. Strangeway, C. Carlson, M. Temerin, J. McFadden, R. Ergun, and W. Peria (2000), FAST observations of upward accelerated electron beams and the downward field-aligned current region, in *Magnetospheric Current Systems*, *Geophys. Monogr. Ser.*, vol. 118, edited by S. Ohtani et al., p. 173, AGU, Washington, D. C.

Ergun, R. (1998), FAST satellite observations of electric field structures in the auroral zone, *Geophys. Res. Lett.*, *25*, 2025.

Ergun, R. E., C. W. Carlson, J. P. McFadden, R. J. Strangeway, M. V. Goldman, and D. L. Newman (2001), Electron phase-space holes and the VLF saucer source region, *Geophys. Res. Lett.*, *28*, 3805.

Ergun, R. E., L. Andersson, C. W. Carlson, D. L. Newman, and M. V. Goldman (2003), Double layers in the downward current region of the aurora, *Nonlinear Processes Geophys.*, *10*, 45.

Goldman, M. V., D. L. Newman, and R. E. Ergun (2003), Phase-space holes due to electron and ion beams accelerated by a current-driven potential ramp, *Nonlinear Processes Geophys.*, *10*, 37.

Gorney, D. J., Y. T. Chiu, and D. R. Croley (1985), Trapping of ion conics by downward parallel electric fields, *J. Geophys. Res.*, *90*, 4205.

Hwang, K.-J., K. A. Lynch, C. W. Carlson, J. W. Bonnell, and W. J. Peria (2006), Fast Auroral Snapshot observations of perpendicular DC electric field structures in downward auroral current regions: Morphology, *J. Geophys. Res.*, *111*, A09205, doi:10.1029/2005JA011471.

Hwang, K.-J., R. E. Ergun, L. Andersson, D. L. Newman, and C. W. Carlson (2008), Test particle simulations of the effect of moving DLs on ion outflow in the auroral downward-current region, *J. Geophys. Res.*, *113*, A01308, doi:10.1029/2007JA012640.

Karlsson, T., and G. T. Marklund (1996), A statistical study of intense low-altitude electric fields observed by Freja, *Geophys. Res. Lett.*, *23*, 1005.

Marklund, G. (2001), Temporal evolution of acceleration structures in the auroral return current region, *Nature*, *414*, 724.

Marklund, G., T. Karlsson, and J. Clemmons (1997), On low altitude particle acceleration and intense electric fields and their relationship to black aurora, *J. Geophys. Res.*, *102*, 17,509.

Moncuquet, M., F. Bagenal, and N. Meyer-Vernet (2002), Latitudinal structure of outer Io plasma torus, *J. Geophys. Res.*, *107*(A9), 1260, doi:10.1029/2001JA900124.

Newman, D. L., M. V. Goldman, R. E. Ergun, and A. Mangeney (2001), Formation of doulbe layers and electron holes in a current-driven space plasma, *Phys. Rev. Lett.*, *87*, 255001, doi:10.1103/PhysRevLett.87.255001.

Newman, D. L., N. Sen, and M. V. Goldman (2007), "Reduced" multi-dimensional vlasov simulations, with applications to electrostatic structures in space plasmas, *Phys. Plasma*, *14*, 55907, doi:10.1063/1.2712423.

Newman, D. L., L. Andersson, M. V. Goldman, R. E. Ergun, and N. Sen (2008a), Influence of supra-thermal background electrons on strong auroal double layers: Vlasov-simulation parameter study, *Phys. Plasma*, *15*, 072902, doi:10.1063/1.2938753.

Newman, D. L., L. Andersson, M. V. Goldman, R. E. Ergun, and N. Sen (2008b), Influence of supra-thermal background electrons on strong auroal double layers: Laminar and turbulent regimes, *Phys. Plasma*, *15*, 072903, doi:10.1063/1.2938754.

Singh, N., and I. Khazanov (2005), Planar double layers in magnetized plasmas: Fine structures and their consequences, *J. Geophys. Res.*, *110*, A04209, doi:10.1029/2004JA010620.

L. Andersson and R. E. Ergun, Laboratory of Atmospheric and Space Plasmas, University of Colorado at Boulder, Campus Box 530,1234 Innovation Dr., Boulder, CO 80303, USA. (laila.andersson@lasp.colorado.edu; ree@lasp.colorado.edu)

K.-J. Hwang, NASA Goddard Laboratory Space Flight Center, Code 673, Greenbelt, MD 20771, USA. (jhwang@helio.gsfc.nasa.gov)

D. L. Newman, Center for Integrated Plasma Studies, University of Colorado at Boulder, Campus Box 390, Boulder, CO 80309-0390, USA. (david.newman@colorado.edu)

J.-B. Tao, Department of Astrophysical and Planetary Sciences, University of Colorado at Boulder, Campus Box 391, Boulder, CO 80309-0391, USA. (jianbao.tao@colorado.edu)